

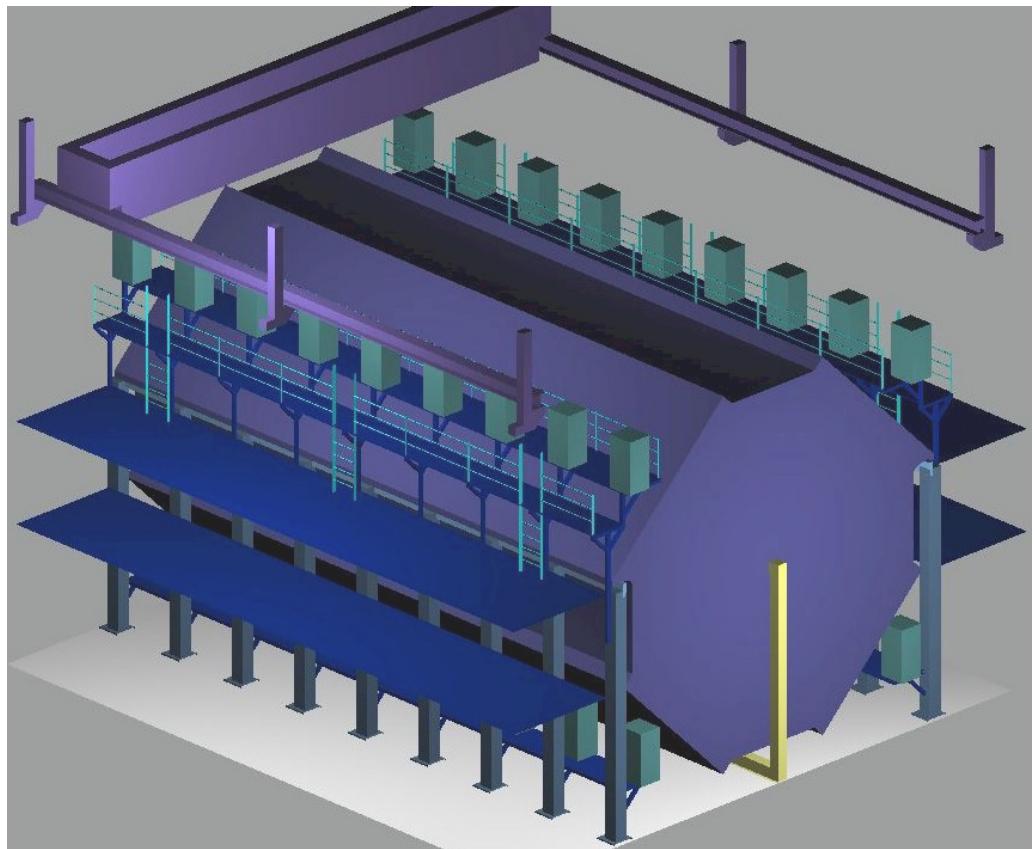
MINOS Scintillator

- Overview
- A few details
- Some cost and production information
- Comments regarding other applications

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NuMI Off-Axis Workshop
SLAC
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The MINOS Far Detector

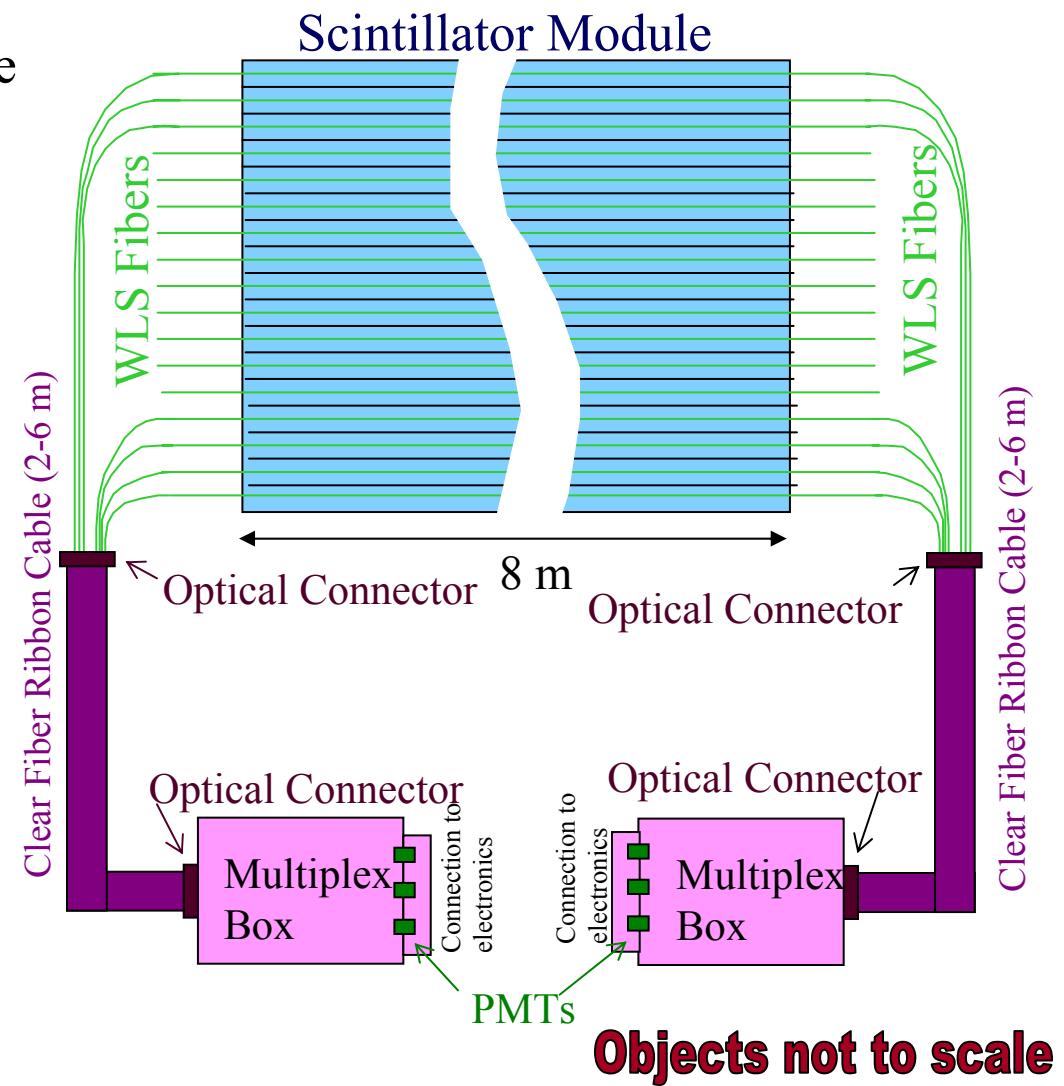
- 8m octagonal steel & scintillator tracking calorimeter
 - Sampling every 2.54 cm
 - 4cm wide strips of scintillator
 - 2 sections, 15m each
 - 5.4 kton total mass
 - $55\%/\sqrt{E}$ for hadrons
 - $23\%/\sqrt{E}$ for electrons
- Magnetized Iron ($B \sim 1.5T$)
- 484 planes of scintillator
 - $26,000 \text{ m}^2$



One Supermodule of the Far Detector...

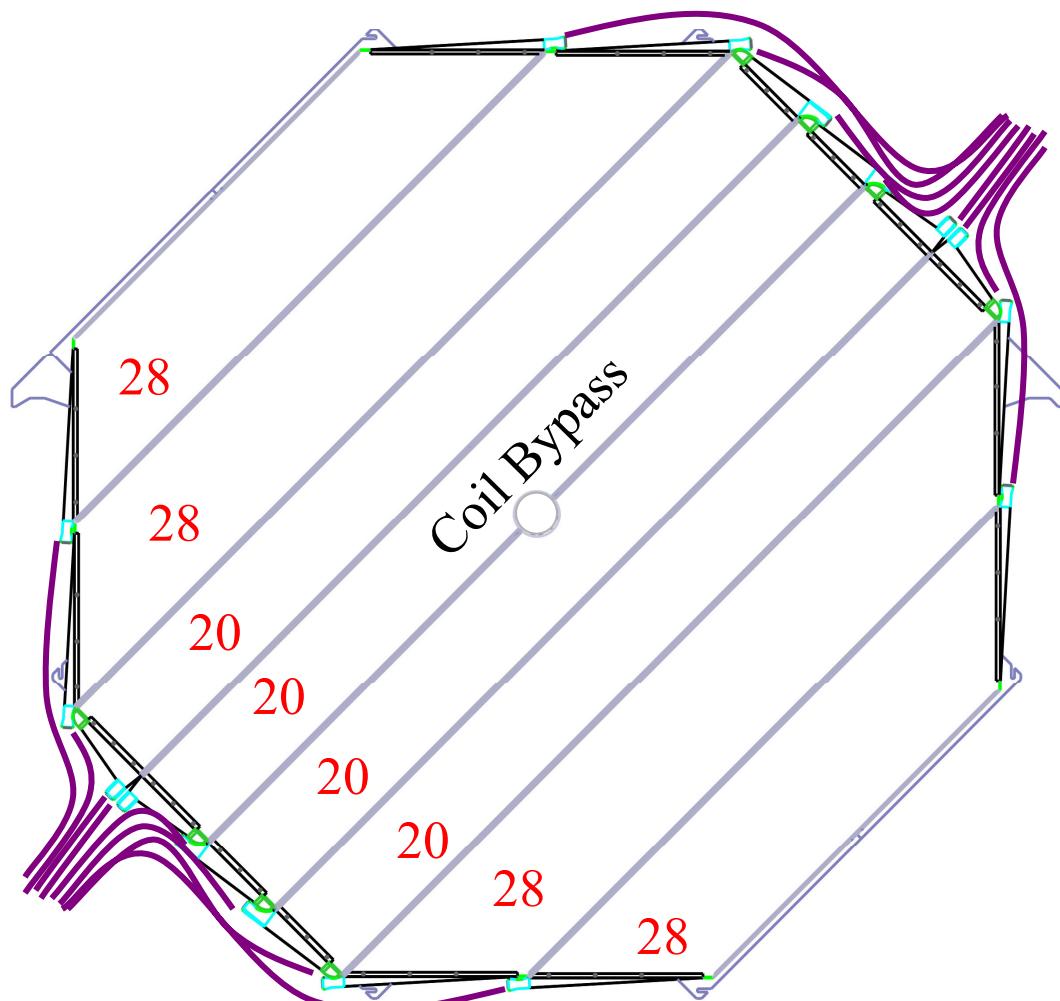
Schematic View of the MINOS Scintillator System

- Extruded scintillator, 4cm wide
- Two-ended WLS fiber readout.
- Strips assembled into 20 or 28-wide modules.
- WLS fibers routed to optical connectors.
- Light routed from modules to PMTs via clear fibers.
- 8 Fibers/PMT pixel in far detector. (Fibers separated by $\sim 1\text{m}$ in a single plane).
- 1 Fiber/PMT pixel in near detector (avoids overlaps).
- Multi-pixel PMTs (Hamamatsu M16)



Far Detector Module Layout

- 8 modules cover one far detector steel plane
- Four 20-wide modules in middle (perp. ends)
- Four 28-wide modules on edges (45 deg ends)
- Two center modules have coil-hole cutout



Design Specifications

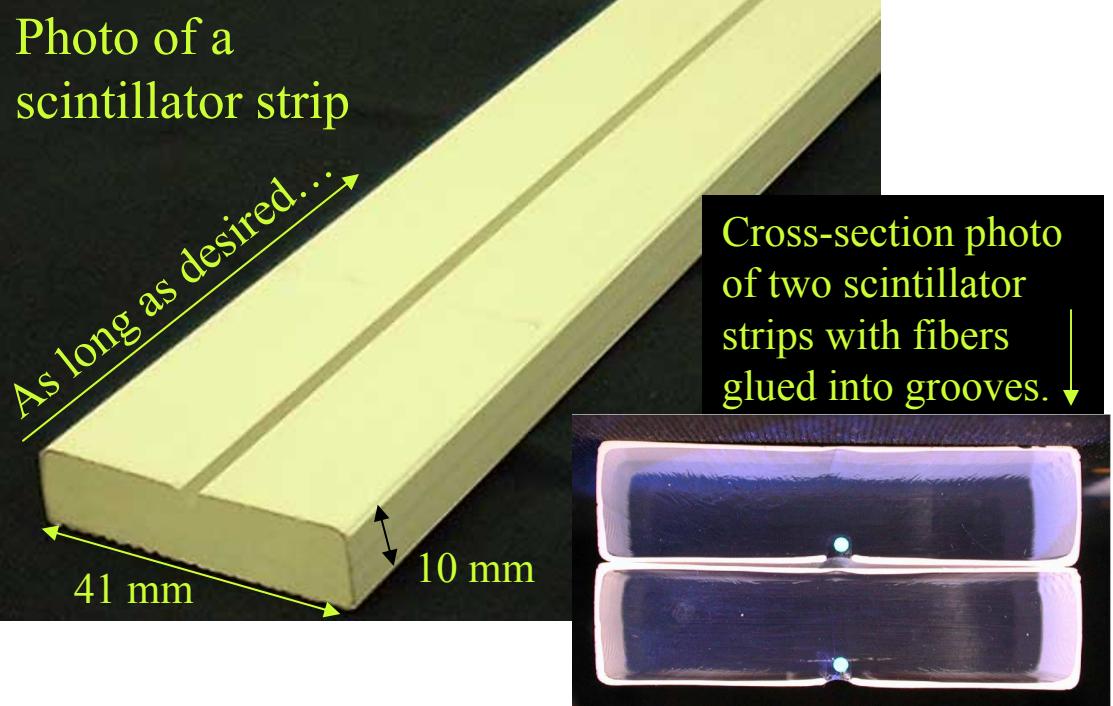
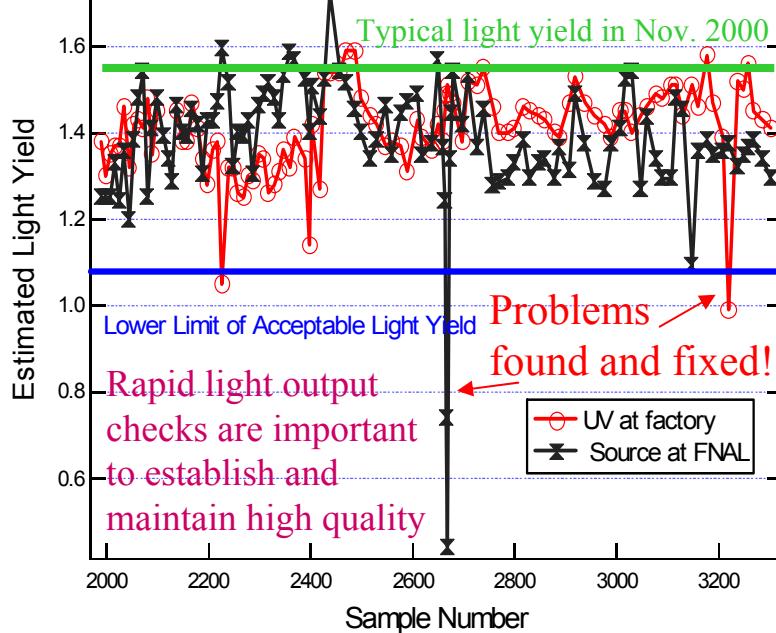
- Observed Light: The light output is set by physics requirements:
 - Hadronic energy resolution $\sigma < 60\%/\sqrt{E}$ requires $n > 0.5 \text{ pe's/mip}$
 - Tracking efficiency $P_\mu > 90\%$ per plane requires $n > 2.5 \text{ pe's/mip}$
 - Complete physics signature simulations requires $n > 2.0-2.5 \text{ pe's/mip}$
- Light output specification based on physics and construction issues:
 - $L_{\text{sys}} = L_{\text{physics}} \times F_{\text{assembly}} \times F_{\text{aging}} \times F_{\text{contingency}} = 4.7 \text{ pe's/mip summed.}$
 - F_{assembly} = assembly variation factor = 1.3
 - F_{aging} = aging factor = 1.2
 - $F_{\text{contingency}}$ = contingency factor = 1.3
- Uniformity: Light output variation $< 30\%$ from nominal response.
- Attenuation: Near/far light ratio < 5 .
- Stability: Light decay time > 10 years.
- Calibration: Relative near/far hadronic energy scale within 2%. 5% absolute.
- Linearity: Linear to within 5% up to 30 GeV of hadronic energy.
- Crosstalk: $< 4\%$ from pixel to pixel.
- Timing: $\sigma < 2 \text{ ns}$ for $> 10 \text{ pe's}$ and 5 ns for $> 2 \text{ pe's}$. Useful for atm. neutrinos
- Transverse pitch: 4.1 cm pitch for pattern recognition on EM showers.
- Modular construction: Easily handled and installed modules.

Some Scintillator System Parameters

- Some major system features
 - Extruded Polystyrene Scintillator: 300 T, 600 km of 4.1x1.0 cm² strips.
 - WLS Fiber: Kuraray double-clad 1.2 mm diam., 175 ppm Y11, 780 km
 - Scintillator Modules: 20/28 strips wide and up to 8m long. ~4300 mods., ~28,000 m²
 - Clear Fiber: Like WLS, no fluor, 1100 km of fiber built into cables with 20/28 fibers.
 - PMTs:
 - Far detector: Hamamatsu M16 with 8 fibers per pixel with fibers readout from each side of the detector. 3 tubes per plane, ~1500 tubes
 - Near detector: Hamamatsu M64 with one fiber per pixel and fibers readout from one side of the detector (with reflectors on the far end). ~200 tubes.
 - Light Injection: Blue LED illumination of all WLS fibers to rapidly track PMT response.
- Performance Requirements:
 - Light output: > 4.7 observed pe's on average for a MIP crossing.
 - Time measurement: $\sigma < 5$ ns per plane for MIP crossing.
 - Calibration:
 - Relative near/far energy response to within 2%.
 - Absolute hadronic energy response to within 5%.

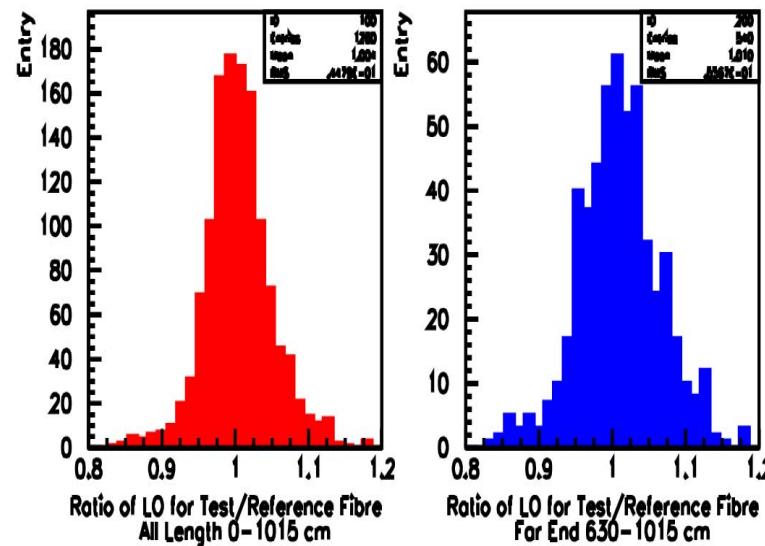
Extruded Scintillator

Production light output measurements



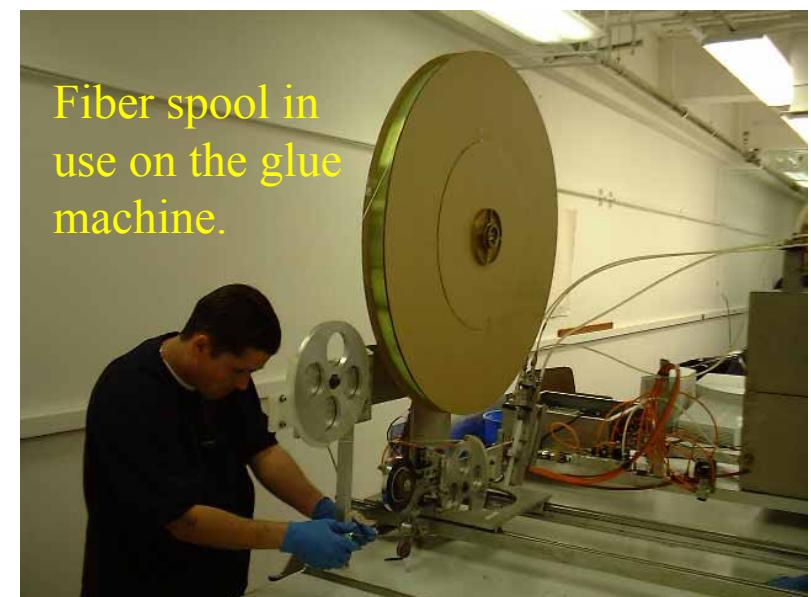
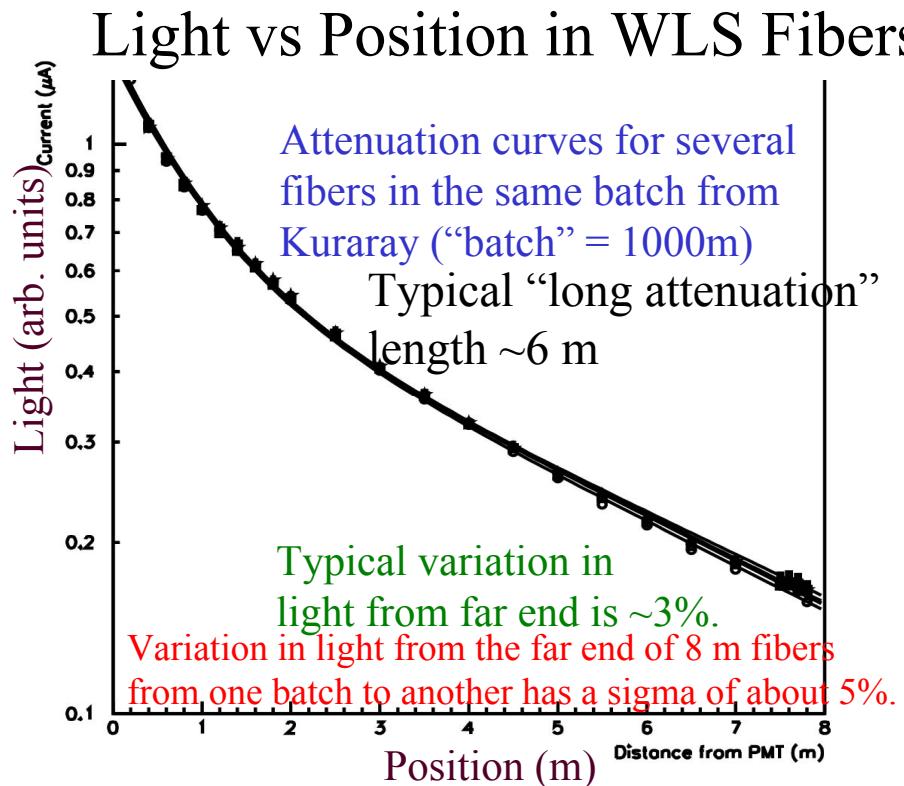
- Dow Styron 663 W polystyrene without additives
- PPO and POPOP waveshifters (1% and 0.03% by weight)
- 1.0 cm x 4.1 cm cross-section extrusion co-extruded with TiO₂ reflector
- Extruded groove for WLS fiber (which is glued into the strip)
- Light output excellent for this collection geometry... better than commercial cast scintillator machined to shape and wrapped with Tyvek.

Relative light output in production fiber sample points



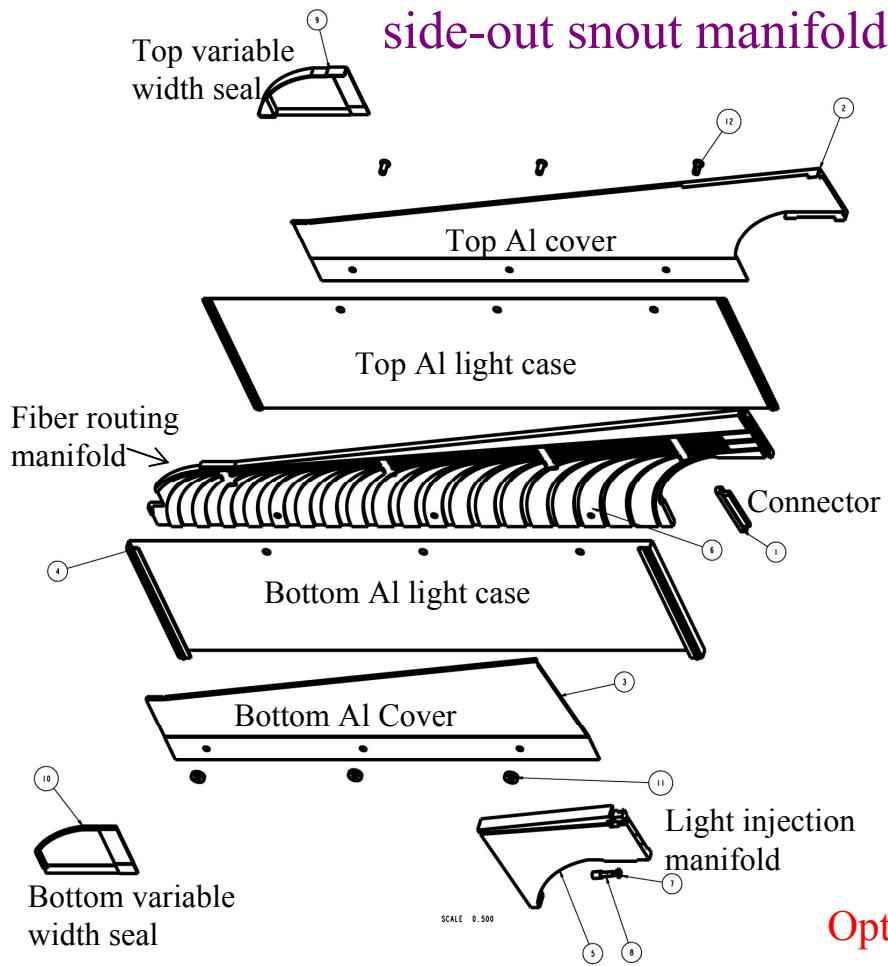
WLS Fiber

- Kuraray WLS fiber:
 - $1.20 +0.024 -0.005$ mm diam.
 - 175 ppm Y11 fluor (K27)
 - polystyrene core, double clad (PMMA and polyfluor)
 - “Non-S Type”
- An excellent product

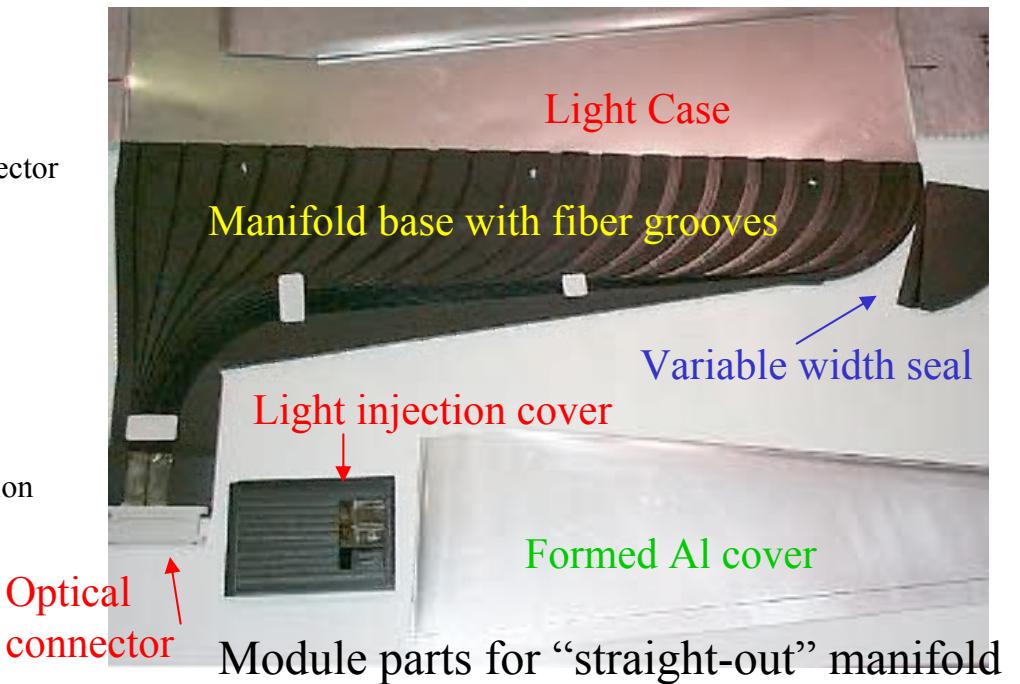


Module Components

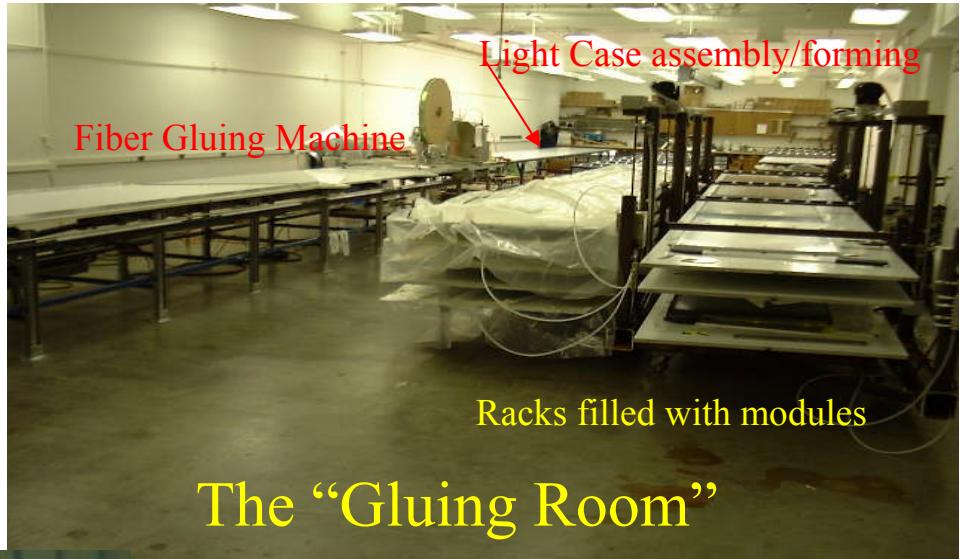
Assembly Drawing for
side-out snout manifold



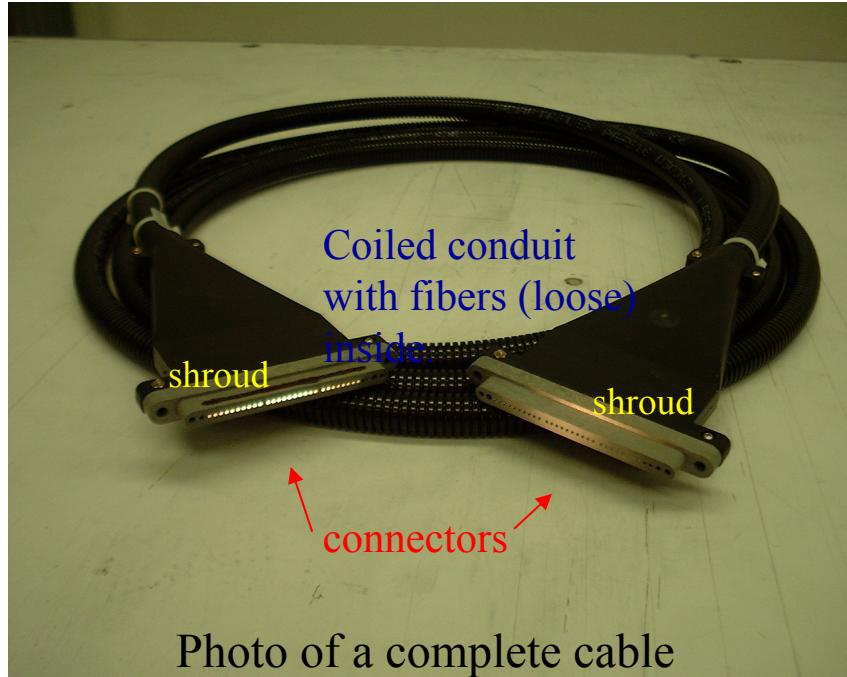
- The scintillator modules are a laminate of scintillator strips (with WLS fiber glued into the groove) with aluminum skins.
- WLS fibers are routed through end manifolds to bulk optical connectors.
- The entire assembly is light-tight.



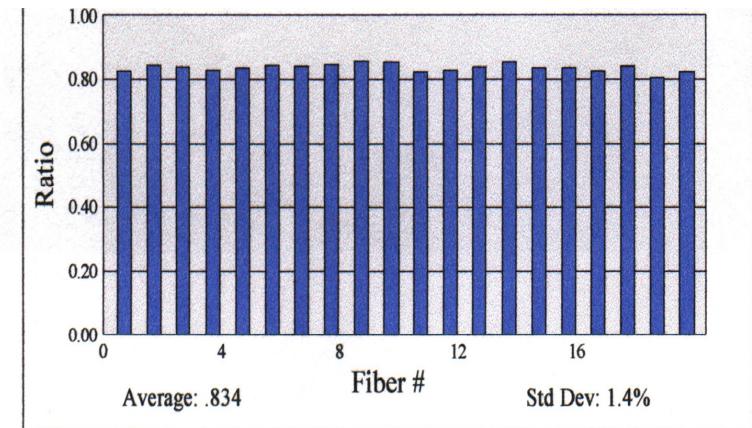
Module Factories



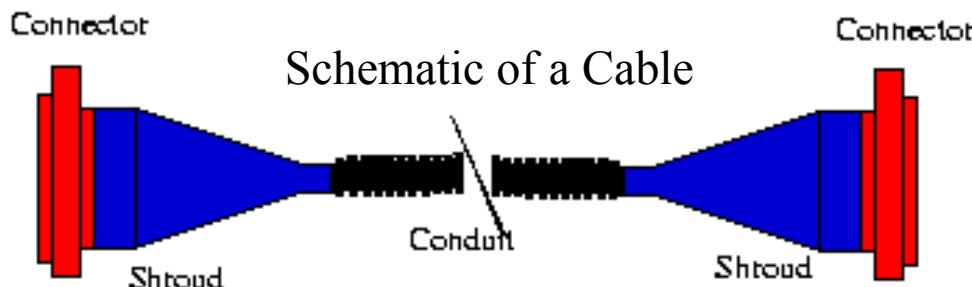
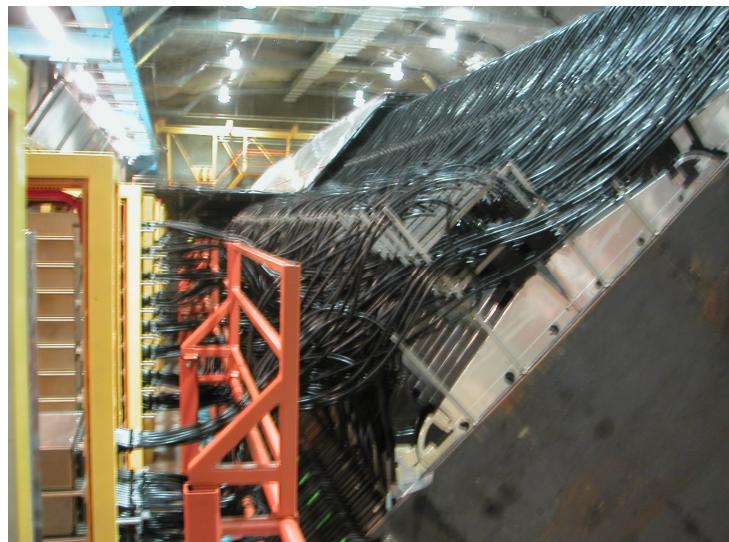
Clear Fiber Cables



Typical response for a 3.5 m long cable compared to a reference 1m cable with ~90% absolute transmission.



Typical attenuation length \sim 14m!

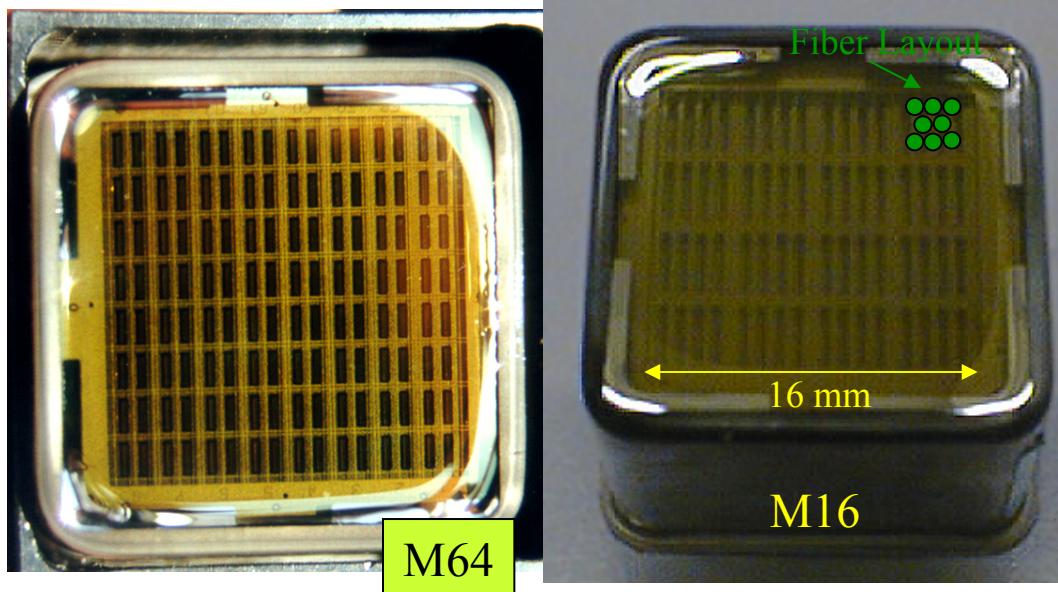


20/28 Fibers per cable
1.2 mm diam. Kuraray double clad fiber

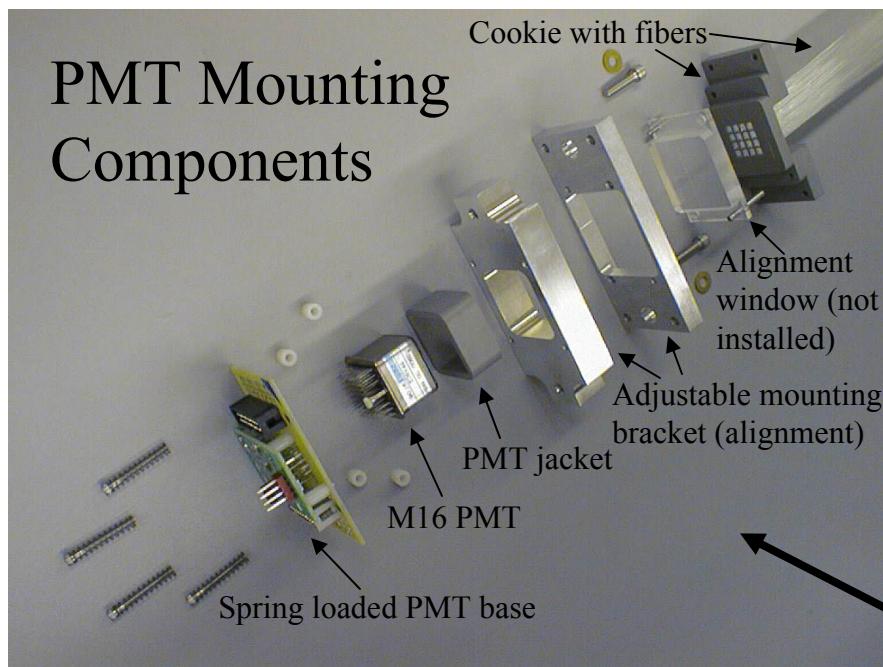
Clear fiber cables transmit light from modules to PMT boxes

PMTs

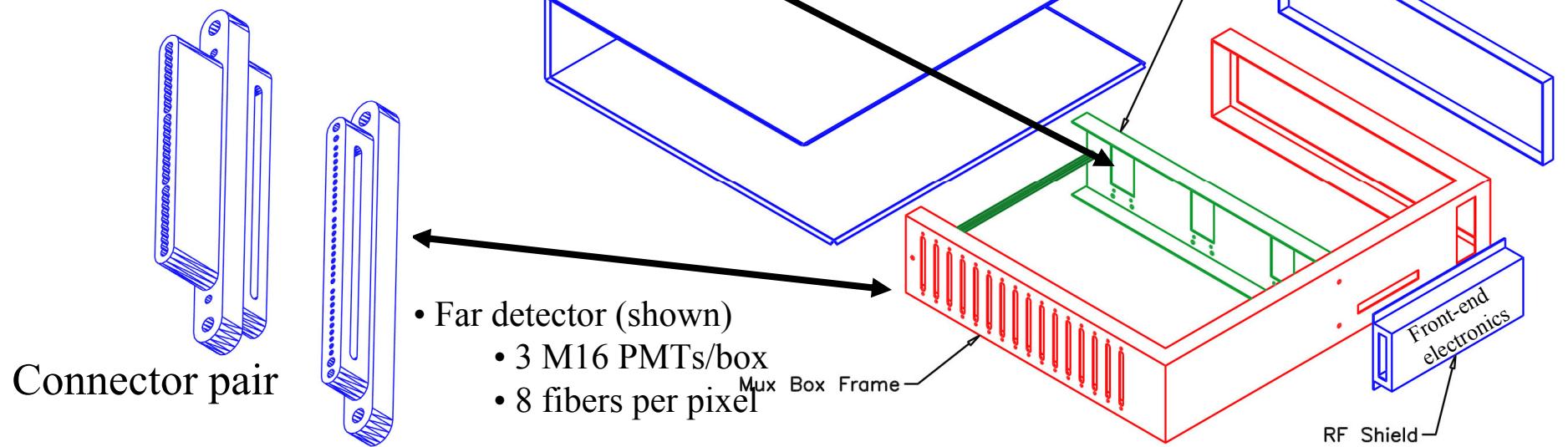
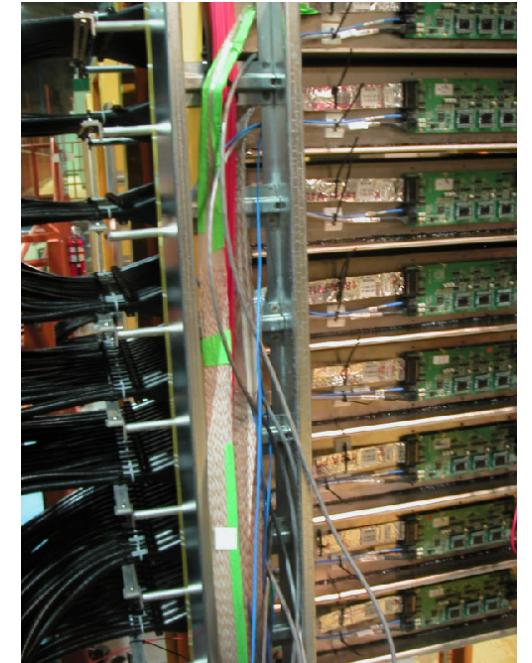
- Hamamatsu R5900 series multi-anode PMTs have been selected:
 - 16 pixel tubes for the far detector (pixel size 4mm x 4mm)
 - 64 pixel tubes for the near detector (pixel size 2mm x 2mm)
- Gain of 10^6 consistent to x2 (M16) or x3(M64)
- QE at 520 nm typically 13.5%
- Good single pe peak
- Very fast signals and low time jitter.



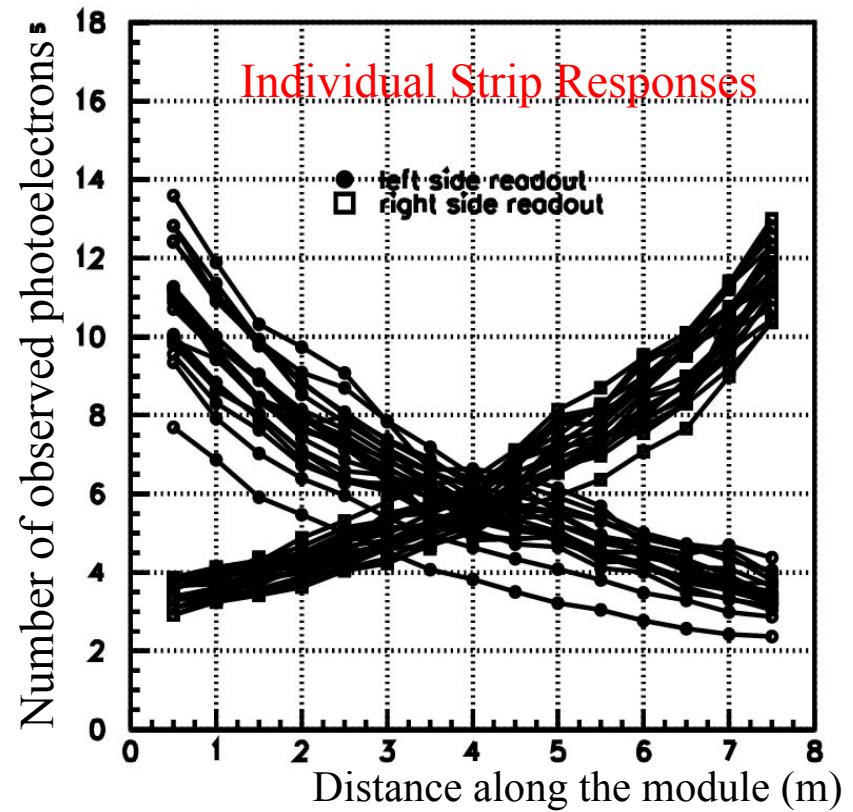
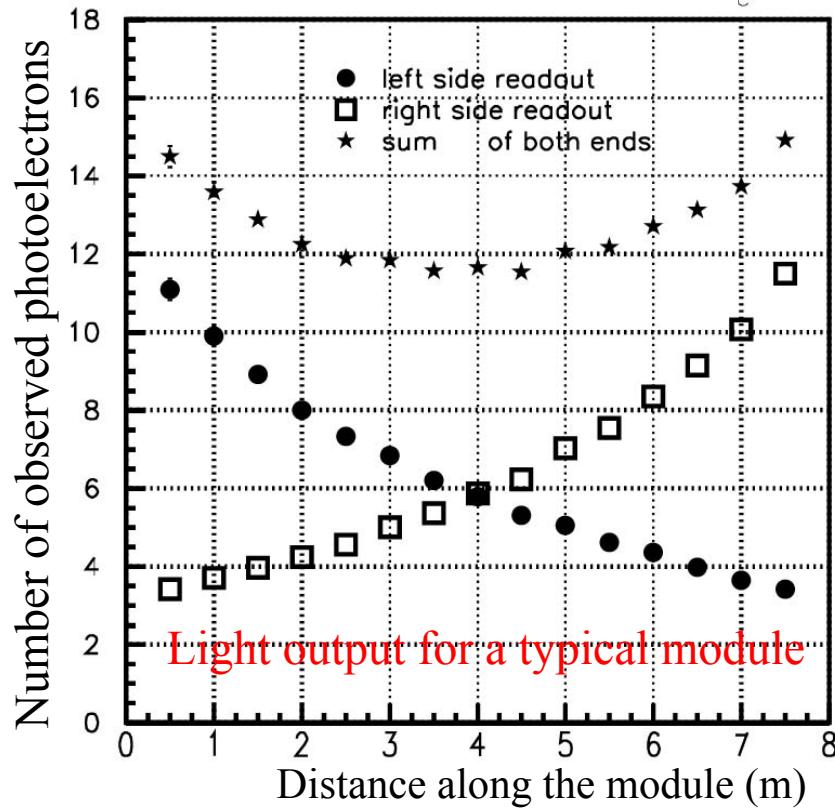
PMT Boxes and Connectors



View of PMT boxes installed on the far detector



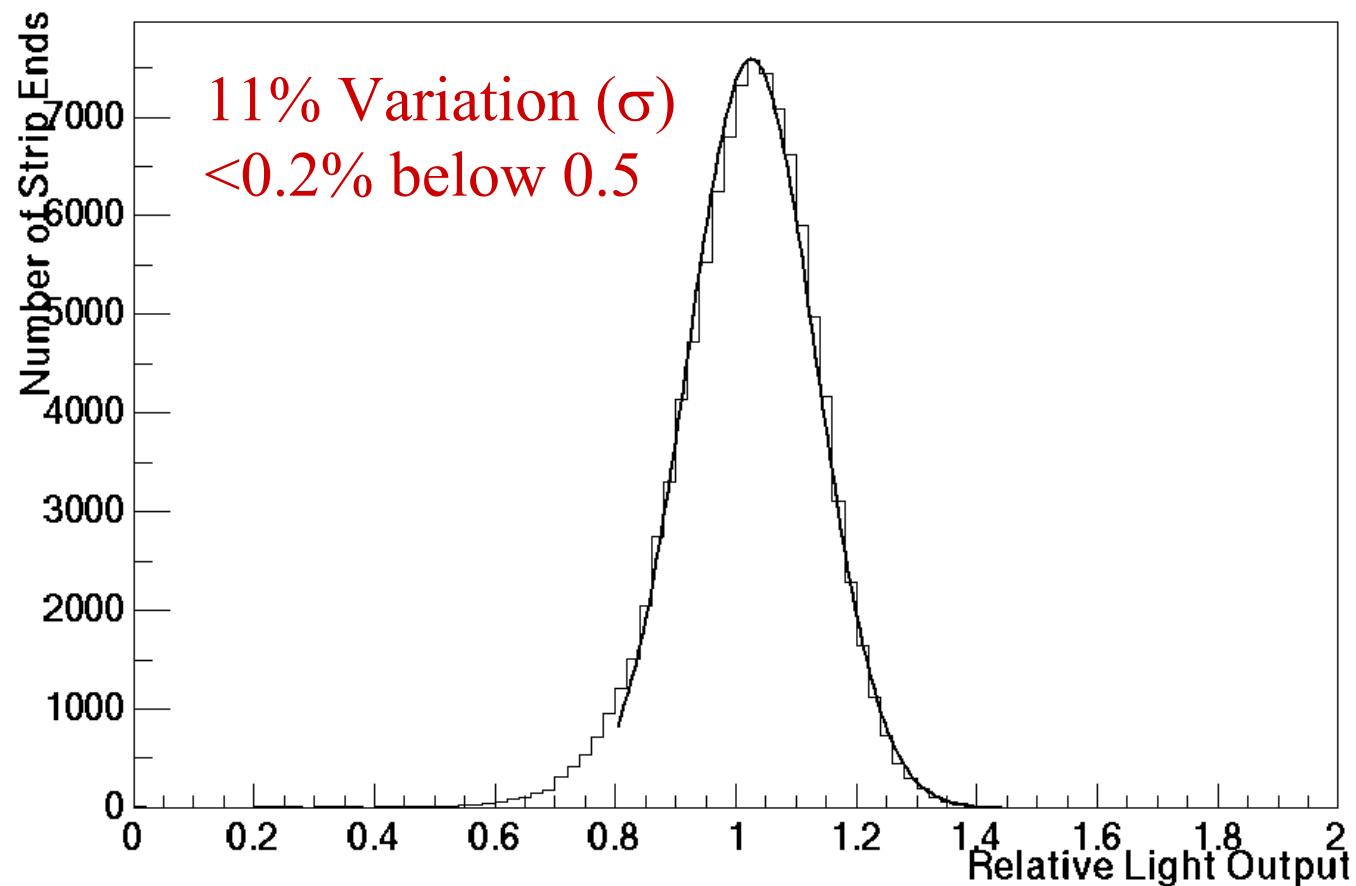
Typical Module Performance



Light output vs position of cosmic ray muons passing nearly perpendicularly through a scintillator module averaged over all strips within a module. The light output is measured using the full MINOS readout apparatus (connectors, clear fibers, PMTs...). The light read from each end of a module is shown along with the sum of light from each end.

Variation in Module Light Output

Relative Light Distribution

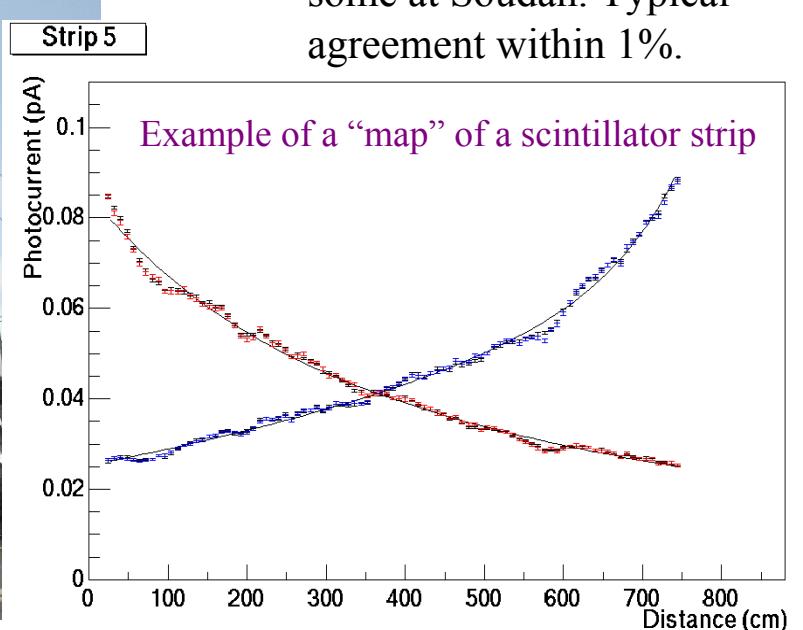


Light output measured from mapping at module centers for far detector modules.

Assembly and Testing at Soudan



- Scintillator system components are assembled at universities and shipped to Soudan.
- Steel and components are sent down the shaft.
- Scintillator modules are mapped at the factories and some at Soudan. Typical agreement within 1%.



Plane Assembly

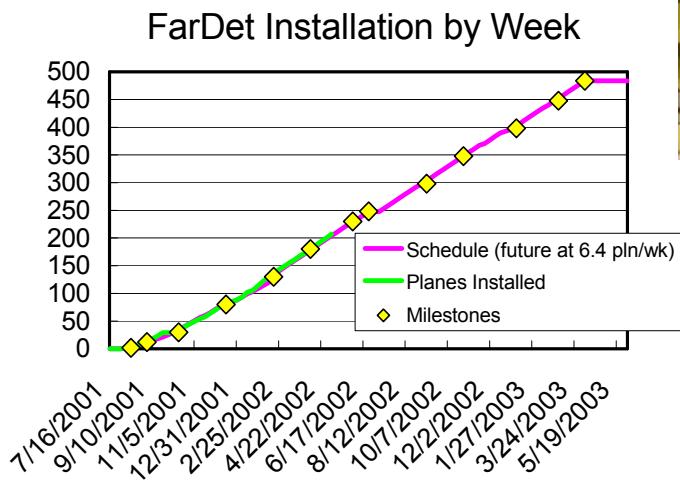


Steel Welded and modules placed.



Crane carries plane down the hall for installation

Planes Installed



Plane lifted to vertical

6-8 Planes per week



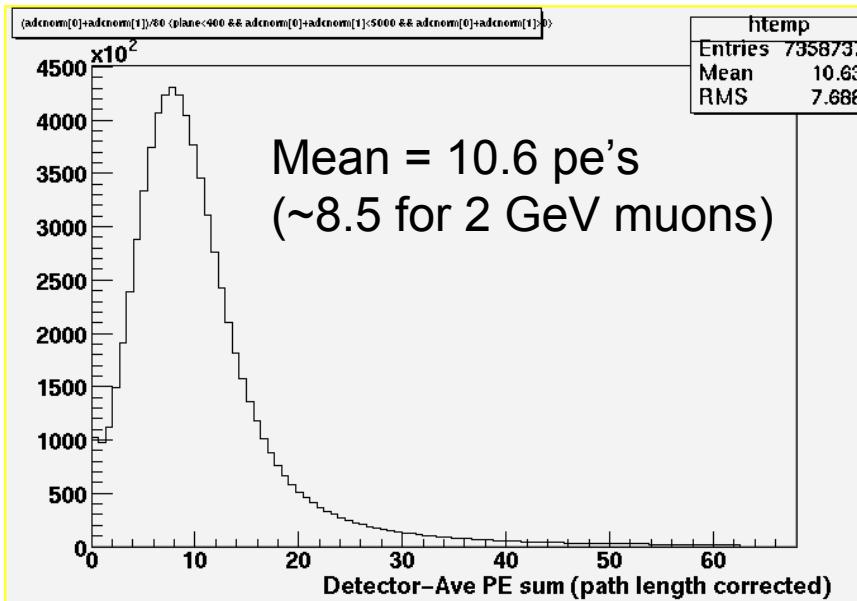
Status of MINOS Construction



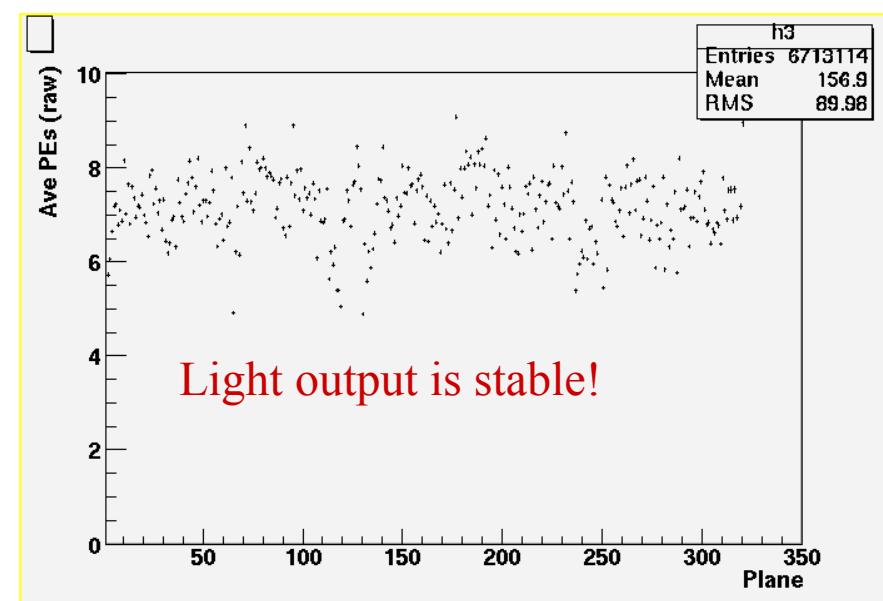
- The far detector is ~80% built and operating.
- The magnetic field is on in the first half.
- The full detector will be complete by July 2003.
- A cosmic-ray veto shield is installed on 1/2 of the detector.
- Cosmic Ray data are being collected for calibration and commissioning.

Light output at the far detector

- The most significant design critereon for the far detector was the light output.
 - >4.7 pe's/muon (2 GeV muons) for the average sum of two strip ends.
- The measured light output is almost a factor of two higher than the design requirement.



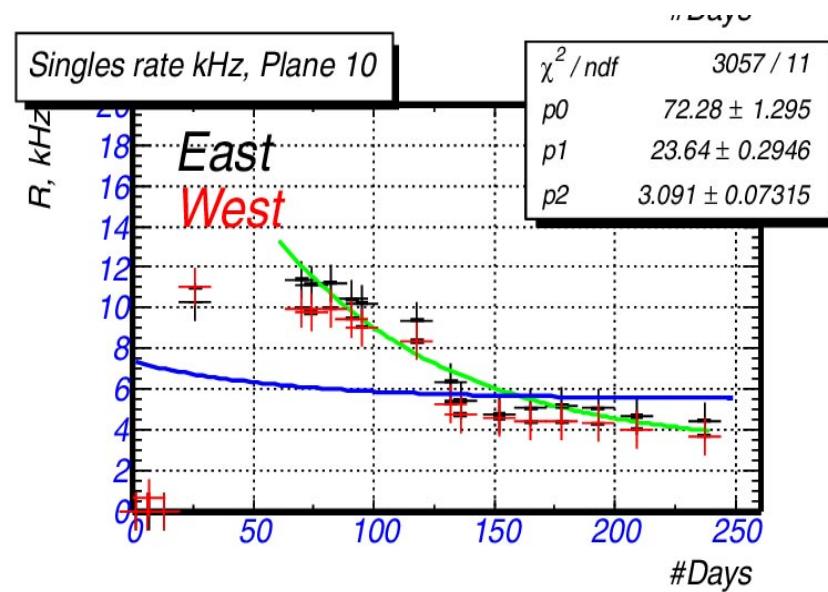
Light output measured for all strips for muons in the far detector. The light output is corrected to 1 cm pathlength per plane but is not corrected for PMT gain variations.



Average light output for one-side of readout vs plane number in the detector. (Not corrected for pathlength or gain variations). This shows the uniformity in the hardware and raw response.

Anomalous Rates in Far Detector

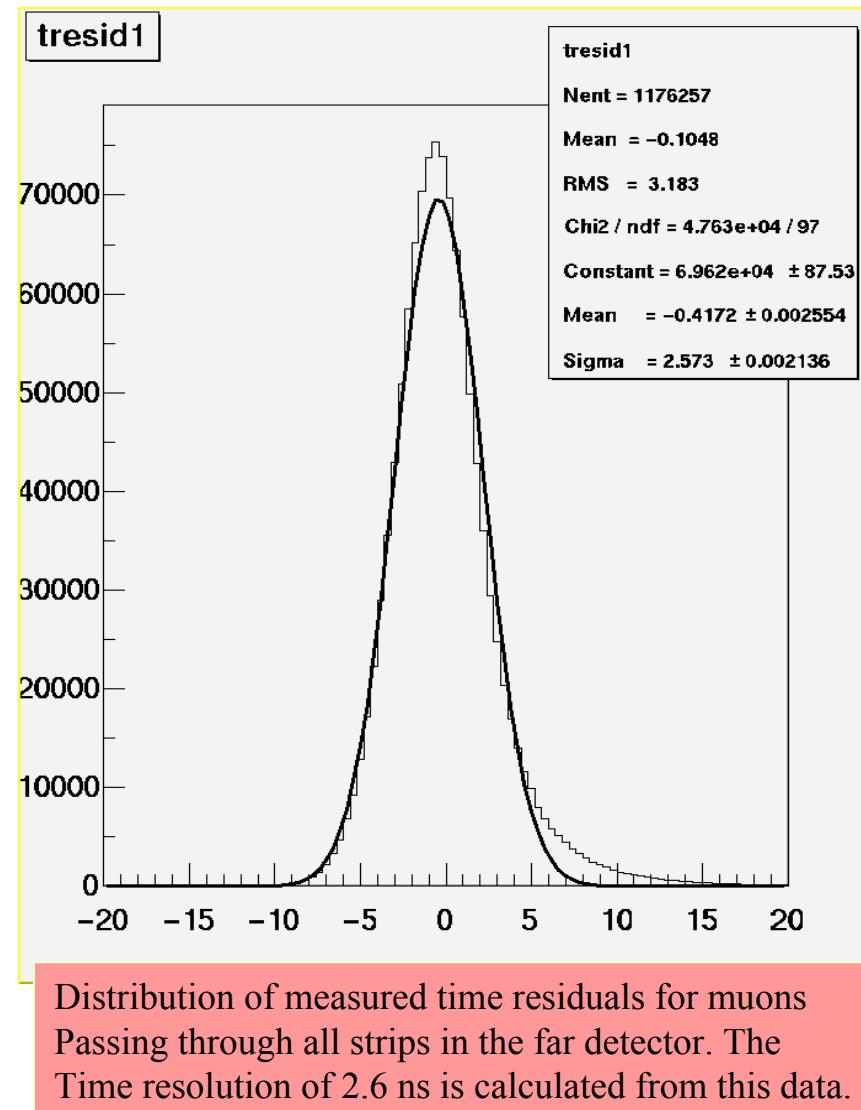
- The expectation before starting far installation was that the rate of single photoelectrons would be about 1 kHz/plane-end and would result from gammas from radioactivity in the cavern walls.
- The detector steel is low radioactivity and shields the modules from most of the background. A plane of modules half exposed to radiation in the hall gives a count rate of ~50 Khz.
- Once a plane is well shielded by several planes of steel, the rate drops, but only to ~10 kHz at first. We have determined that this rate is primarily due to some kind of slow decay of spontaneous light from the WLS fiber. We do not know why the light is produced.
- After several months, the rate is down to about 4 kHz per plane-end. Will it continue to drop?



A typical single pe rate from one plane end as a function of time.

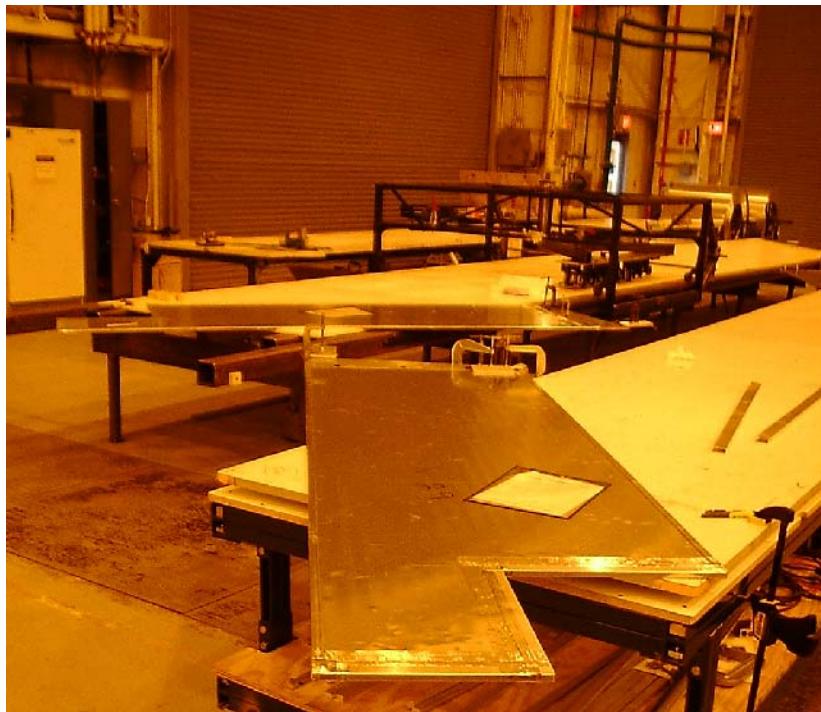
Time Resolution in the Far Detector

- The time resolution of the MINOS scintillator system is determined primarily by the decay time of the Y11 fluor in the WLS fiber ~ 8 ns.
- The time resolution for each scintillator strip is expected to be ~ 2.5 ns based on the photoelectron statistics for muons.
- Current measurement of resolution using downgoing muons in the far detector is $\sigma=2.6$ ns/plane.
- The direction of muons can be determined with ~ 10 planes for contained vertex events.
- To distinguish upgoing from downgoing through-going muons ~ 20 planes are needed.

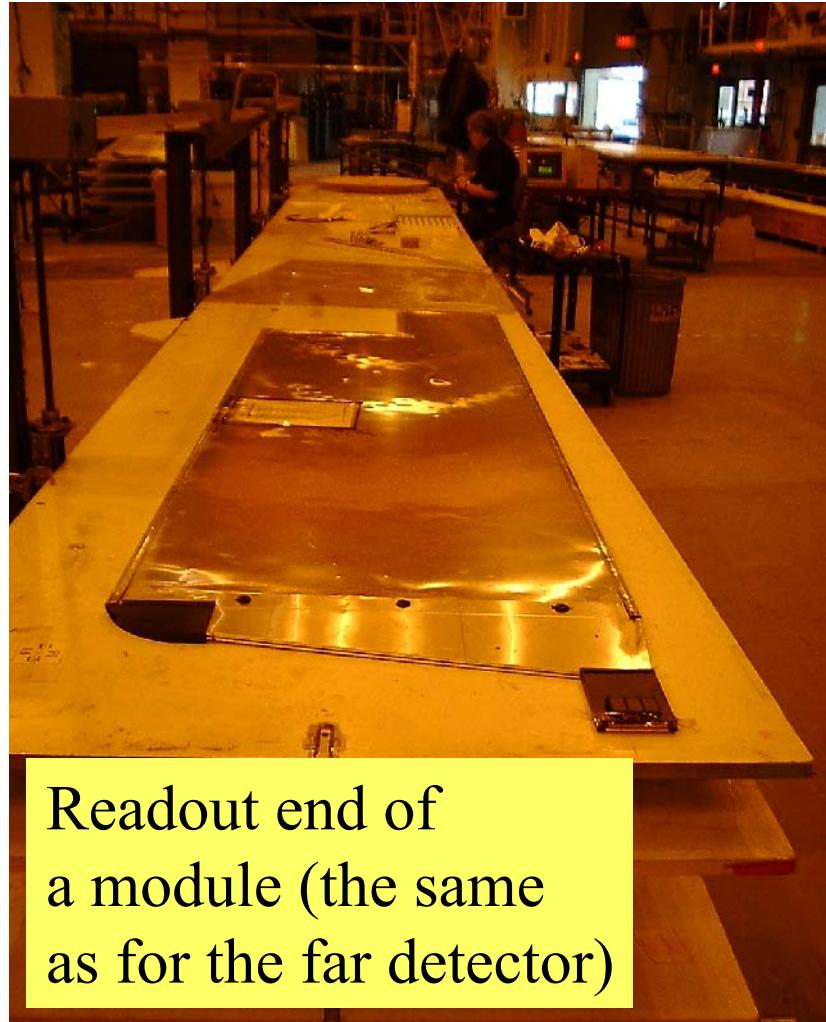


MINOS Near Detector "Cutoff" Modules

MINOS near detector modules have single ended readout.

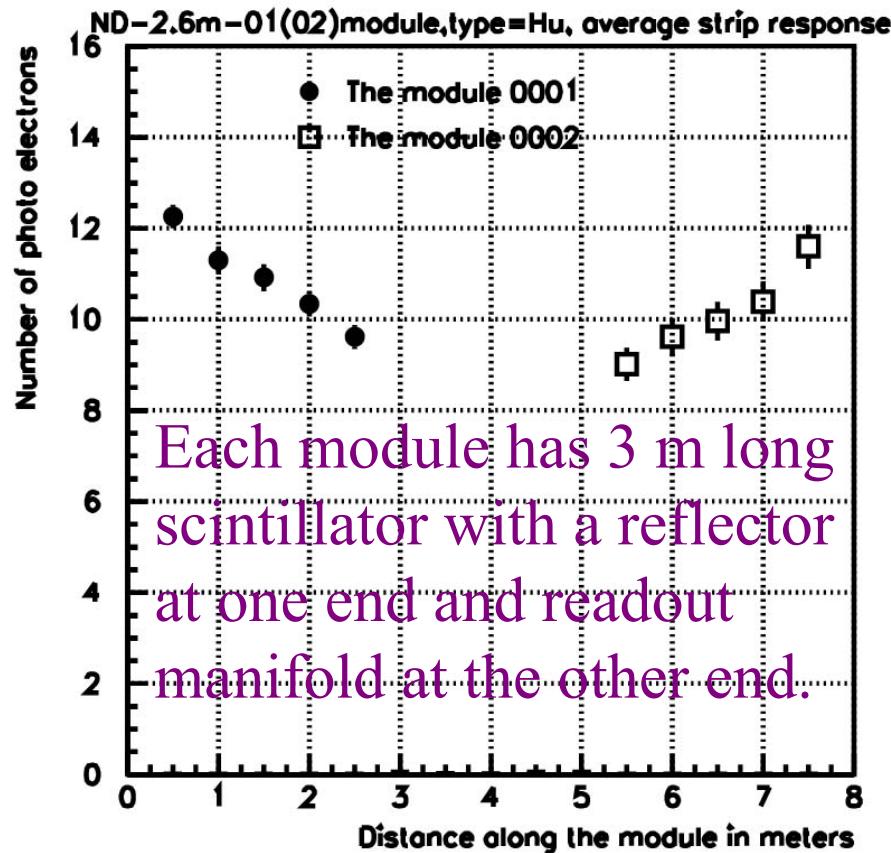


Cutoff end of a module.
Strips are cut perpendicularly
at the necessary length and
“reflector tabs” are glued on.

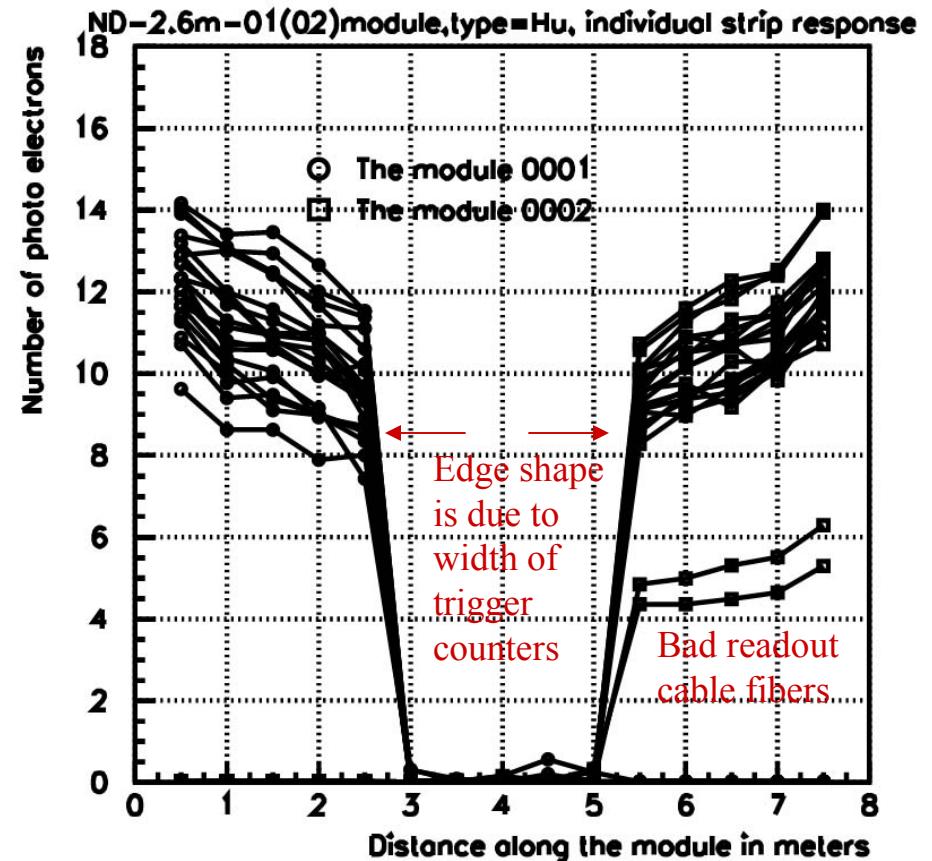


Readout end of
a module (the same
as for the far detector)

Light output measurements from Near detector modules



Average response of two near detector modules.



Strip-by-strip response of the same two modules

Responsibilities for production of Scintillator System Components

- Most of the scintillator system components are provided by commercial suppliers:
 - WLS and clear fibers (Caltech and Indiana responsible for purchasing)
 - Module components (Minnesota responsible for purchasing)
 - Scintillator strips (Fermilab responsible for purchasing and production tasks)
 - PMTs (Texas and Oxford responsible for purchasing)
- We have several production tasks which are handled “in house”.
 - Production of assembly equipment (Argonne, Fermilab, Caltech, Minnesota).
 - Scintillator module production (Caltech and Minnesota (Far) and Argonne (Near))
 - Testing of PMTs (Texas, Oxford, Athens)
 - Production of MUX boxes (Indiana, RAL, Tufts).
 - Production of clear fiber cables (Indiana, Texas A&M, James Madison, UCL)
 - Production of light injection system (Sussex, UCL)
 - Oversight for component acquisition (Fermilab, Argonne, Caltech, Minnesota, Texas, Indiana, UCL,...)

Average university costs ~0.6 average lab costs for same work but not always possible for all aspects of the work to be done.

Overview of Costs (Far Detector Only)

	EDIA/Setup \$k	Production \$k	Total \$k
• Scintillator System	2950	12100	15050
– Scintillator	750	2430	3180
– WLS Fiber	220	1170	1390
– Module Components	400	1400	1800
– Module Fabrication	1100	2400	3500
– Clear Fiber Cables	100	2090	2190
– PMTs	180	1670	1850
– PMT Boxes	200	940	1140
• Readout Electronics (32k channels)			4500
• Steel	1000	3500	4500
• Installation	1000	3800	4800
• Cavern/outfitting			12000
• Scintillator system cost/m ²		\$470	\$580
• Scale-up by factor of ~4?		\$330	\$400

MINOS Building Blocks

- Scintillator Module Components
 - Extruded Scintillator
 - MINOS Cost = \$9/kg (about 2 m) includes QC checks, handling, delivery.
 - New die ~\$10k
 - New profile ~\$50-100k (depends on how radical the changes are)
 - New vendor ~\$100k+ (depends on competence of vendor)
 - Kuraray: MINOS quote ~\$13/kg... MINOS did not accept. This was the only competing offer.
 - WLS Fiber:
 - MINOS cost = \$1.55/m
 - On average need $L_{scin} + 0.7m \times (1,2)$
 - Small production cost ~ \$3.50/m (~10km)
 - Cost scales as $\sim R^2$ and light as $R^{1.3}$. Biggest practical radius was good value for MINOS but maybe not if lower light is OK. MINOS fiber is 1.2 mm diameter. 1.4 mm is probably the largest possible using these techniques.

More MINOS Building Blocks

- Scintillator Module Components (cont.)
 - Aluminum ~ \$12/m² of module (2 skins)
 - Manifolds, etc ~ \$200/module (~\$5-10k startup for different styles)
 - Glues, expendables ~\$12/m² of module
 - Connectors ~\$5/ module
- Scintillator Module Assembly
 - ~20 hours/module for MINOS, style of module matters very little
 - Setup for different style modules ~ 2 weeks = 800 hours
 - Setup with MINOS equipment at new site and new crew ~ 4000 hours
 - New equipment equivalent to MINOS ~ \$400k.
 - Cost at Caltech rate for MINOS ~\$400/module
- Full module costs:
 - MINOS Cost: \$660/module + \$180/m² : 8m module = \$2100 = \$260/m²

More MINOS Building Blocks

- Readout Component Costs
 - Clear fiber cables
 - \$1.15/m for raw clear fiber
 - \$1.00/m for conduit
 - \$8/ cable for connectors and shrouds
 - 2 hours/cable assembly labor (~\$44/cable)
 - Example: 24 fibers x 4m = \$170
 - PMTs
 - M16 ~ \$760/tube + \$40/base + \$200/mounting +\$400/routing box = \$1400/tube
 - In MINOS far detector: \$1400/tube = \$88/pixel = \$11/fiber end readout (8fib/pix)
 - M64 ~ \$1300/tube + \$50/base + \$200/mounting + \$400/routing box = \$1950/tube
 - In MINOS near detector: \$1950/tube = \$30/pixel = \$30/fiber end readout (1fib/pix)
 - Other stuff: (LEDs, HV...) ~\$200k for a “small” system
 - Electronics:
 - MINOS far detector: ~\$400k + \$40/channel (pixel, \$5/fiber end)
 - MINOS near detector ~\$600k + \$200/channel (pixel/fiber end)
 - DAQ system ~\$300k

Some Design Considerations

- MINOS construction techniques are flexible. One can adjust strip widths, thickness, fiber diameter, module sizes and shapes, readout geometry... Many things are possible but cost money to develop and provide proper assembly tooling.
- Light output will be an important issue. Some rough scaling rules:
 - Light output <linear with scintillator thickness but depends on aspect ratio.
 - Light output inversely proportional to strip width (actually about 1.8x for 2 vs 4 cm.)
 - Light output with two fibers = 1.8x light with one fiber.
 - Light output vs fiber radius $\sim R^{1.3}$
- I believe that MINOS-style scintillator will work just fine “outdoors” in northern Minnesota. This could be proven relatively easily.
- Due to the size of our construction project, MINOS spent a relatively large amount of money in EDIA and tooling in order to make our production efficient. The tooling costs for one of the MINOS scintillator factories were about \$500k. Should we be thinking about saving some of this tooling? Time is very tight!
- Production at university groups is both highly effective in terms of getting work done and very cost effective. I estimate that the cost for the MINOS scintillator system would have been 40% higher if done completely at somewhere like Fermilab.

Conclusions

- The MINOS scintillator system is the largest area “active” detector built for a single particle physics experiment:
 - 28,000 m² of scintillator at \$580/m²
 - Compare to ~18,000 m² streamer tubes in MACRO at cost ~\$400/m² for 3 cm pitch with two views.
 - Compare to ~2800 m² of liquid scintillator for MACRO at cost ~\$1500-\$2000/m² for 70 cm pitch but with much more light output (~500 pe's/mip)
- The production and performance are a great success. We have roughly exceeded the design requirements for light by x2. This was not obvious in advance. Lesson: Industrialized production eventually permits very good quality control.
- The cost per unit area for a scintillator detector for MINOS are much lower than earlier scintillator systems... perhaps additional savings of ~30% for larger scale production of exactly the same thing.
- Additional savings should be possible if one reduces the light output requirements. But one also will need technical changes to really bring the cost down.
- I think this detector needs *no* building. I think we should prove it.